INTERACTION REGION CORRECTION EXPERIENCE AT LEP

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Abstract

I briefly review the corrections applied to the interaction region of LEP with a view to what might be relevant to the LHC.

1. INTRODUCTION

As something of a phoenix rising from the decommissioning of LEP, the LHC necessarily shares some characteristics of its illustrious leptonic progenitor. Yet the two machines differ to the extent that most of the matters discussed so far in this workshop have been irrelevant in the design and operation of LEP! Having been asked to review the experience in correcting the LEP interaction region, I can only ask: are there aspects of interaction region correction at LEP, not discussed so far in this workshop, that might have some bearing on the LHC?

More specifically, the two machines have the same circumference and a similar number of magnetic elements (per ring in the case of the LHC); each is subject to similar movements of the very same tunnel floor and each has superconducting interaction region (IR) quadrupoles. On the other hand, their beams, their energies, their magnetic field strengths and most of their hardware components are radically different.

I cannot do more than mention the main points in this brief, informal summary. I hope it will be taken as a set of pointers to the fuller information that you can find through the references.

2. LINEAR OPTICS

The standard set-up of LEP's physics optics includes a correction of the vertical Twiss function at each IP to its nominal value $\beta_y^* = 0.05\,\mathrm{m}$. This is done very simply by measuring the change in tune for small changes of the IR quadrupole strengths. The same quadrupoles are then trimmed to rematch β_y^*.

On many occasions, adjustments of β_y^* and errors of the IR quadrupoles have been related to β-beating and phase advance errors measured around the ring. Corrections of the interaction region cannot be considered in isolation. For a recent example, see [1].

Compensation of the betatron coupling due to the experimental solenoids is also a routine matter, modulo minor historical glitches. The compensation by means of nearby tilted quadrupoles is computed by the standard technique of zeroing the off-diagonal blocks of an appropriate transfer matrix. The basis of the calculation is a model in which the measured longitudinal field profile of each solenoid is obtained using several slices of solenoid interspersed with slices of IR quadrupole. This procedure works well.

3. NONLINEAR DYNAMICS

Thanks, mainly, to the synchrotron radiation, the physical effects determining the dynamic aperture in LEP are utterly different from those in hadron rings like RHIC or the LHC. At high energy, the dominant non-linear fields causing large amplitude particles to be unstable are those of the chromaticity correction sextupoles, the accelerating fields of the RF cavities and the *designed quadrupole gradient* of the interaction region quadrupoles [2]. (In LEP, quadrupoles must be considered as *nonlinear* elements because the radiation loss in them is $\propto p^2 K_1^2 (x^2 + y^2)$ where p, x and y are a particle's momentum and transverse coordinates and K_1 the quadrupole gradient.)

Although we know the multipole components of the superconducting interaction region quadrupoles from the magnetic measurements [3,4], they are not strong enough to make any significant difference to the dynamic aperture [5]. This was the case, both for the original set of quadrupoles (MQC type) installed for LEP1 operation (up to 65 GeV per beam) and the stronger ones (MQCC type) that replaced them for LEP2 (up to 100 GeV).

A MAD description of the multipole gradients of the MQCCs is available in the standard repository of files describing the LEP optics.

At the highest energies, the gradient of the interaction region quadrupoles is limited by the radiative beta-synchrotron coupling instability. The only ways to overcome this effect are to increase the RF voltage, which is no longer possible, or to reduce the strength of the interaction region quadrupoles. Thus, this instability translates into a lower limit on b_y^*. Since this instability arises because of the radiation damping, there is no corresponding effect in the LHC.

4. ALIGNMENT OF BEAM POSITION MONITORS

Beam-based alignment techniques have been used extensively at LEP to measure the offsets between beam position monitors and quadrupole magnets [6,7,8]. The favored technique is the so-called "K-modulation" in which a quadrupole gradient is modulated at a frequency well below the betatron frequency. Moving the closed orbit in the quadrupole to minimize the response locates the magnetic center and determines the offset of an adjacent beam position monitor.

This method revealed [7] that there were indeed substantial misalignments between the magnetic centers of the quadrupoles and the beam position monitors. The offsets for the first generation of the superconducting quadrupole magnets for LEP (MQC type) show large offsets of up to $-2\,\mathrm{mm}$. Their replacements for LEP II (MQCC type) have offsets only up to $-1\,\mathrm{mm}$.

It goes without saying that, once these offsets were taken account of in the orbit measurements, there were clear benefits for machine operation and performance.

5. MOVEMENTS OF IR QUADRUPOLES

At three of LEP's four IPs, the innermost quadrupole (QS0) is imbedded deep inside the detector and supported from the main tunnel floor by a cantilever structure (see Figure 1). At the fourth (IP2, for the L3 detector) the three innermost quadrupoles (QS0, QS1A and QS1B) are supported together with the inner parts of the detector in a 32 m long support tube. This tube can be moved with motorized jacks.

Because of movements of these support structures, vertical orbit correction is the most frequent task carried out by the operators during physics fills. In 1994 for example [7], over 13000 vertical corrections were done during physics data-taking, or while setting up for it. The orbit corrector magnets near QS12 and QS8 in the experimental straight sections were by far the most popular correctors, not surprisingly since they are at a vertical phase difference of $n\pi$ from the low-β quadrupoles. (At the time, the orbit correction algorithms were programmed to avoid using other correctors nearer the IP).

As by far the strongest quadrupoles in LEP, the interaction region quads are the dominant source of orbit and optical errors. Because there is a vertical phase advance $\Delta\mu_y \approx \pi$ between them, these occur according to well-known patterns depending on the symmetry of the movements around the IP.

Serious attention has to be given to the correction of these linear effects. A few years into LEP operation, hydrostatic leveling systems were added to monitor their movements [7]. Other systems, based on differential pressure in water columns and potentiometers that measure relative movements of luminosity monitors and main detectors, provide further information. Careful analysis of the results, taking out the effects of applied orbit corrections, showed strong correlations between measured movements of the QS0 quadrupoles and computed orbit correction kicks [8].

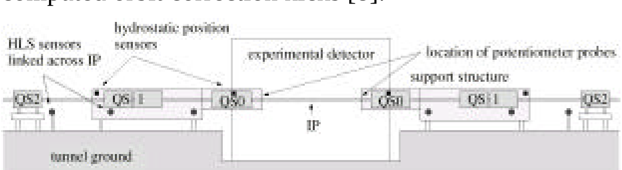

Figure 1: Interaction region around an experimental detector (not to scale), reproduced from [8].

6. BEAM SEPARATIONS

Another important class of corrections associated with the interaction regions in LEP is related to the separations of the beams at the collision point. Generally, these could be corrected by adjusting the electrostatic separation at the IPs. In LEP, there are three different physical origins of separation between beams:

1. **Applied electrostatic fields** designed to separate the beams in some part of the machine (e.g., at different times, the horizontal pretzel scheme used to separate in the arcs or the local vertical bumps near the IPs used in a "bunch-train" scheme).
2. **Synchrotron radiation**. The two beams have different orbits because of the interplay between the strong energy loss by synchrotron radiation in the arcs and its replacement by clustered RF cavities. These so-called "energy-sawtoothing" effects cause the beams to have different momentums at the same place in the ring, and therefore different orbits (for further discussion, see [9]).
3. **Beam-beam effects**. Different bunches in the same beam can experience different sequences of beam-beam forces resulting in different orbits; these are similar to the so-called "PACMAN" effects in hadron colliders. These were particularly pernicious in the "bunch-train" scheme because there was no means to correct them, except in an average sense, to maximize the luminosity over all bunch encounters [10].

7. OPTICAL DIFFERENCES BETWEEN BEAMS

In the LHC, the two beams circulate in different vacuum chambers. Despite being closely related thanks to the twin-bore magnet design, the magnetic fields acting upon them can be somewhat different. Thus, in principle, their optics can be different. In LEP, despite being in the same vacuum chamber, subject to essentially the same magnetic (and some electric) fields, the two beams have different optics because of the energy-sawtoothing (the same physical origins as the orbit separations discussed above). In practice, corrections are difficult to make for this kind of effect. The operators try to keep the distribution of RF voltage as symmetric as possible. At top energy, however, there is little reserve voltage left to provide much latitude for this. Fortunately, however, there is usually enough symmetry in the distribution of accelerating voltage that differences in b_y^* between the beams are generally small, of the order of 5 %.

Some detailed measurements and calculations, with illustration of the effects of synchrotron radiation on the optical functions around the ring, can be found in [11].

8. CONCLUSIONS

Although there is no need to correct higher-order multipoles in the superconducting low-β quadrupoles, several other, more basic, corrections of LEP's interaction region are important. The quadrupoles move with their support structures, generating closed-orbit displacements. To equalize luminosity and minimize the dominant source of errors in the linear optics, the optical functions at the interaction points have to be corrected by adjusting the gradients. Beam-based alignment has been very important in determining the misalignment of the magnetic centers of the beam-position monitors relative to those of the quadrupoles themselves. One can hardly overstate the need to pay close attention to alignment of machine components in the interaction region of the LHC and to provide effective means to cope with any misalignments that arise after all.

Another class of corrections are those associated with differences of orbits and optics between the beams. Generally these can be corrected or lived with. The worst class of effects are differences between different bunches of the same beam. We should not forget that these can also arise in the LHC and may be very difficult to deal with.

REFERENCES

[1] G. Morpurgo, "Do we understand the luminosity imbalance?", Proceedings of the 9th Workshop on LEP Performance, Chamonix, 1999, CERN-SL-99-007 DI (1999) and

http://www.cern.ch/CERN/Divisions/SL/publications/chamx99/PAPERS/GM8_1.PDF

[2] See, e.g., J.M. Jowett, "Realistic Prediction of Dynamic Aperture and Optics Performance for LEP", Proc. 1999 Particle Accelerator Conference, New York City, 29 March - 2 April 1999,

http://ftp.pac99.bnl.gov/Papers/Wpac/TUP86.pdf

and references therein.

[3] P.J. Ferry et al, "Analysis of the Performance of the Eight Superconducting Quadrupoles for the LEP Low-Beta Insertions", Proceedings of the 11th International Conference on Magnet Technology, Tsukuba, Japan, Elsevier 1989, pp. 253–8.

[4] A. Ijspeert, T.M. Taylor, M. Begg, "Construction and Test of Superconducting Quadrupoles for the LEP2 Low-Beta Insertions", Proceedings of the Fourth European Particle Accelerator Conference, London 1994, World Scientific, 1994, pp. 2277–9.

[5] There does not seem to be a published reference on this point. I know that it has been checked independently by A. Verdier and Y. Alexahin for different optics. It is also plausible based on a comparison of the magnitudes of kicks due to these multipoles (at amplitudes close to the dynamic aperture) with those due to the lattice sextupoles.

[6] I. Barnett et al, "Dynamic Beam Based Calibration Of Orbit Monitors At LEP",

[7] Frank Tecker, "Methods of Improving the Orbit Determination and Stability at LEP", Ph.D. Thesis, RWTH Aachen, March 1998, PITHA 98/7.

[8] F. Tecker, "Low-Beta Quadrupole Movements As Source Of Vertical Orbit Drifts At LEP", CERN-SL/96-40 (BI), 1996.

[9] J.M. Jowett, "Beam Dynamics at LEP", Proceedings of the Advanced ICFA Beam Dynamics Workshop on "Beam Dynamics Issues for e^+e^- Factories", Frascati, 20–25 October 1997, Frascati Physics Series, 1998.

[10] M. Böge et al, "Measurements of Collision Offsets and Difference in Vertical Dispersion at the LEP Interaction Points", Proceedings of the European Particle Accelerator Conference, Sitges 1996, IOP Publishing, 1996.

[11] J.M. Jowett, "Effect of RF Configuration on β_y^* Measurements in LEP", CERN SL MD Note 240 (1997).